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Detection of SiO Maser Emission in V838 Mon

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Abstract

We report on the detection of 43 GHz SiO maser emission in V838 Mon, a prototype of a new class of eruptive variables, in which a red supergiant was formed after the nova-like eruption in 2002. The detection of SiO masers indicates that the star formed after the eruption is indeed a kind of cool mass-losing object with circumstellar masers. The measured radial velocity and the intensity of maser emission are consistent with the object being located at the distance of about 7 kpc from the sun. It also suggests that a considerable percentage of SiO masing objects in the Galaxy are formed in the same mechanism as that created V838 Mon.

Key words: general — radio lines: stars — AGB and post-AGB stars: circumstellar matter: stars – novae, cataclysmic variables

1. Introduction

V838 Monocerotis is a star erupted in the beginning of January 2002. After developing an A–F supergiant spectrum at the optical maximum phase in a few months, it reveals a cool M-type supergiant spectrum and remains bright in infrared (Munari et al. 2002; Crause et al. 2003), appealing to a prototype of a new class of eruptive variables (Kimeswenger et al. 2002). Though a spectacular discovery of a light echo and succeeding observations of the expansion received large attentions (Bond et al. 2003; Crause et al. 2005), it did not help much to derive an accurate distance to this object due to its model dependence (Tylenda 2004). Instead, based on kinematic and other information, the distance to this object has been estimated to be 8–10 kpc (Munari et al. 2005).

A presence of a B3V hot companion (Munari et al. 2005) at the post-outburst (and likely pre-outburst ; Tylenda et al. 2005a) phase supports a binary-star model of the system. Soker & Tylenda (2003) found that thermonuclear models cannot explain the eruption but a stellar merger can account the outburst luminosity. Tylenda et al. (2005a) argued from the available observational data prior to the eruption that the progenitor of V838 Mon was not an evolved red giant, but a main sequence star being erupted into an M-supergiant.

A number of molecular bands such as CO, H_2O, and TiO have been detected in absorption in infrared (Evans et al. 2003; Lynch et al. 2004). More recently, Rushton et al. (2005) found variable SiO first-overtone emission at 4 μm, which indicates a characteristic of cool supergiant. A search for circumstellar molecular emission at radio wavelengths (in the SiO $J=2$–1 $v=1$ line, and the ^{12}CO $J=1$–0, 2–1, and 3–2 lines) gave negative results (Rushton et al. 2003).

In this paper, we report on the SiO maser detection toward the unusual eruptive variable, V838 Mon. The observations made in a two-month separation (February and April, 2005) indicate that the SiO maser intensity is increasing at current phase. The detection of SiO masers in this object implies that some percentages of stellar maser sources, which have been considered to be mass losing stars at the Asymptotic Giant Branch (AGB) phase (or occasionally post-AGB phase), can be created by the same mechanism as that created V838 Mon. We discuss on the implication of this result in section 3.

2. Observations and Results

The first observation of V838 Mon with Nobeyama 45-m telescope was made on 2005 February 23 in the SiO maser lines ($J=1$–0, $v=1$ and 2) at 43.122 and 42.821 GHz, respectively. The half-power full beam width (HPFBW) was about 40$''$ at 43 GHz. We used a cooled SIS-mixer receiver ($T_{\rm sys} \sim 180-250$ K) and acousto-optical spectrometers with high (40 kHz; AOS-H) and low (250 kHz; AOS-W) resolutions having 2048 channels each. The spectrometer arrays covered velocity ranges of ± 390 km s^{-1} and ± 800 km s^{-1} in AOS-H and AOS-W with effective velocity resolution of 0.3 and 1.8 km s^{-1} per binned channel, respectively. The conversion factor of the antenna temperature ($\equiv T_a^*$) to the flux density was ~ 2.9 Jy K^{-1}. The detail of observations with this system had been described elsewhere (for example, Deguchi et al. 2000).

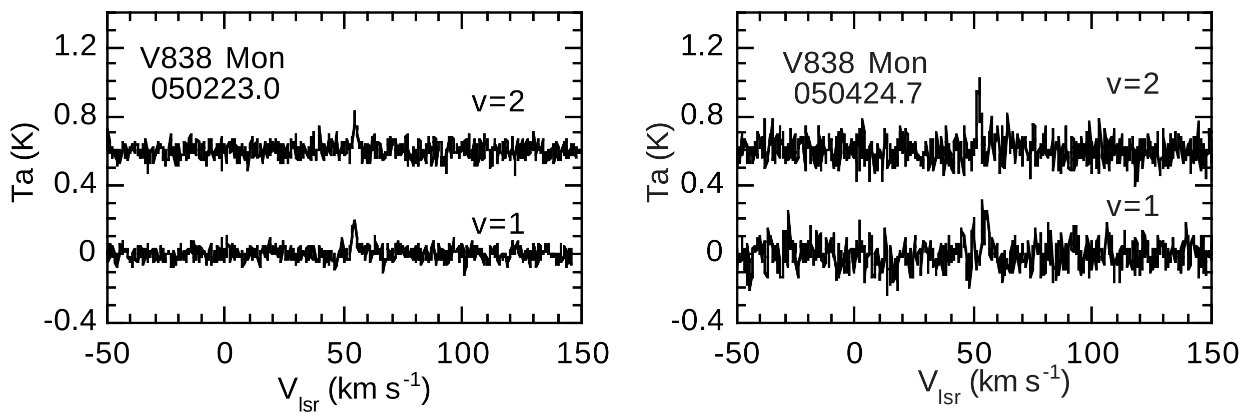

Fig. 1. Spectra of the SiO $J=1$–$0, v=2$ (top) and $v=1$ line (bottom) in V838 Mon. The observation dates are 2005 February 23 (left panel) and 2005 April 24 (right panel).

We detected SiO maser emission in both $J=1$–0 $v=1$ and 2 transitions at $V_{LSR}\sim 54$ km s^{-1} in V838 Mon in about 11 minutes on-source integration time. The spectra taken in AOS-H are shown in figure 1. The detections were confirmed in AOS-W spectra in all cases. The line properties are summarized in table 1, which contains the source name, observed positions, observed transitions, radial velocities ($V_{\rm LSR}$), peak antenna temperatures ($T_{\rm a}$), integrated intensities, and rms noise levels for both transitions from the AOS-H spectra. The MSX 6C catalog (Egan et al. 2003) gives no point source detected within $10'$ of V838 Mon in all of the observed bands, although the MSX imager shows a slight enhancement of emission in A (8.3 μm) band at the position of IRAS 07015−0346 (=V838 Mon; $F_{12}=0.25$ Jy; see van Loon et al. 2004). The 2MASS images (Cutri et al. 2003) do not show any contaminating bright red objects within $1'$ of V838 Mon. Therefore, there is no chance of contamination by other objects emitting SiO masers within a telescope beam.

A short follow-up observation with the same telescope was made on 2005 April 24 for V838 Mon in the SiO $J=1$–0, $v=1$ and 2, and $J=2$–1, $v=1$ (86.243 GHz) lines. The AOS-H spectrometer arrays covered the radial velocity range between ± 75 km s^{-1} in the 86 GHz SiO maser observation. The system temperature was approximately 240 K at 86 GHz. The conversion factor of the antenna temperature to the flux density was inferred to be approximately 4.4 Jy/K at 86 GHz. The $J=1$–0 $v=1$ and 2 maser lines around 43 GHz were found to become slightly stronger than before, but the $J=2$–1 $v=1$ line was not detected.

Figure 1 and table 1 indicate that the SiO maser intensity in V838 Mon apparently increased with time in a two-month span. Though the calibration of the line flux involved uncertainty of about $\pm$ 20% in the NRO 45 m telescope system (for example, see Kamohara et al. 2005), and the noise level was high in the 2005 April observation due to time restriction, the maser intensity in 2005 April seems to increase by about 50 % compared with the intensity in 2005 February. It is consistent with the fact that the 4 μm SiO first-overtone emission was first developed in a periphery of the extended atmosphere during 2002–2003 (Rushton et al. 2005), and after a year or two the outflowing gas made SiO masers at the outer envelope. An outflow velocity of 20 km s^{-1} gives a crossing length of about 6×10^{13} cm over a year, when the gas reaches to the radius of $\sim 1.6\times10^{14}$ cm if it started at the photospheric radius of 1.0×10^{14} cm, which was measured in the near-IR interferometer at 2.2 μm (Lane et al. 2005).

In addition, we observed the same type of eruptive variable, V4332 Sgr (Martini et al. 1999; Banerjee et al. 2004) on 2005 March 9 and 10 by the SiO $J=1$–0 $v=1$ and 2, and added the negative results in table 1. This star, V4332 Sgr, was erupted in 1994 February, developing early M-type spectrum involving TiO bands (Tylenda et al. 2005b). The distance was inferred to be a few kpc away from the Sun. No maser was detected in this star. The 2MASS database shows a faint red star with $K=10.99$ and $H-K=0.61$ at this position.

3. Discussions

3.1. Radial Velocity, Maser Intensity, and Kinematic Distance of V838 Mon.

The radial velocity of SiO maser emission is known to coincide with that of the central star within a few km s^{-1} (Jewell et al. 1991). It directly indicates the velocity of a cool M-supergiant, which was formed after eruption. The relatively narrow (~ 5 km s^{-1}) widths of both maser lines suggest that the turbulence in the outflowing envelope of the M supergiant is relatively mild. The SiO maser lines are normally formed at a few stellar radii of the photosphere for M-type stars ($\sim 10^{14}$ cm; Cotton et al. 2004), but for supergiants, VLBA observations indicate that it is slightly outer part of the envelope (Miyoshi 2003). The SiO maser line profiles of V838 Mon do not show any indication of the broad line width which is common for supergiants(Cernicharo et al. 1997). This is partly due to

Table 1. Observed line intensities

Object	RA(J2000)* h m s	Dec(J2000)* ° ′ ″	Transition mol, J_u–J_l, v	$V_{\rm LSR}$ (km s^{-1})	Peak $T_{\rm a}$ (K)	Integ. int. (K km s^{-1})	rms (K)	obs.date yymmdd.d
V838 Mon	07 04 04.85	−03 50 51.1	SiO 1–0, 1	54.6	0.197	0.577	0.034	050223.0
			SiO 1–0, 2	54.2	0.251	0.396	0.042	050223.0
			SiO 1–0, 1	53.5	0.330	0.813	0.070	050424.7
			SiO 1–0, 2	54.1	0.419	0.681	0.065	050424.7
			SiO 2–1, 1	...	...	...	0.034	050424.7
V4332 Sgr	18 50 36.70	−21 23 29.6	SiO 1–0, 1	...	...	...	0.052	050310.3
			SiO 1–0, 2	...	...	...	0.068	050310.3

* : Positions were taken from the SIMBAD database [originally from Brown et al. (2002) for V838 Mon, and Downes et al. (2001) for V4332 Sgr].

the low signal-to-noise ratio of the detected lines, in which the profile is not enough to reveal the weak broad pedestal feature often seen in supergiants.

The radial velocity of V838 Mon was not accurately known though it has been estimated from P-Cygni-type optical spectra (Kipper et al. 2004; Tylenda et al. 2005a) as $V_{\rm helio}$ = 55–65 km s^{-1} (corresponding to $V_{\rm LSR}$ =42–52 km s^{-1}). The SiO radial velocity found in the present paper, $V_{\rm LSR}$=54 km s^{-1}, coincides with the high end of the optical velocities, establishing the accurate stellar radial velocity. Tylenda et al. (2005a) listed the radial velocities of interstellar clouds within $\sim 1.5^\circ$ from V838 Mon. From their table 3, we find that two molecular clouds, G217.7+2.4 and G218.7+1.8 (=IC 466 or S288), which have the highest radial velocities in the table ($V_{\rm LSR}$ =54.8 and 56.8 km s^{-1}), have the similar radial velocities as that of V838 Mon. The kinematic distances to these clouds were evaluated to be 7.02 and 7.17 kpc, respectively (Wouterloot and Brand 1989). Jiang et al. (1996) estimated the kinematic distances of SiO maser sources in this direction using the rotation curve derived by Burton (1988). Their figure 8 gives the kinematic distance of about 7 kpc for $V_{\rm LSR}$ =54 km s^{-1}, suggesting that V838 Mon is located at the similar distance with these molecular clouds (if V838 Mon is a disk population).

The intensity of SiO maser lines, 0.6 – 1.2 Jy, is comparable with the intensities of masers found in the galactic center and bulge (e.g., see Deguchi et al. 2002; Deguchi et al. 2004a). Therefore, this fact also supports the large distance ($\sim$ 7 kpc) of V838 Mon, provided that the M-supergiant of V838 Mon emits a similar intrinsic maser flux as the bulge SiO maser sources. However, because only maximum (upper limit) of SiO maser line intensity relative to the IRAS 12 μm flux density (i.e., normalized by the luminosity and the distance of the object) is meaningful in general (because of time variation of maser intensity; Jewell et al. 1991), we cannot completely deny the possibility of smaller distance merely based on the line fluxes. The measured flux density is nearly equal to the value expected from the maximum photon fluxes of the usual SiO sources at the distance of 7–8 kpc, indicating that the envelope of an M-supergiant in V838 Mon radiates SiO masers at a nearly maximum flux among masing objects.

3.2. Eruptive Formation of Maser Stars

Though the interstellar matter revealed in the light echo of V838 Mon and a diffuse middle infrared emission found in MSX map were claimed to be a past activity of AGB phase of the progenitor of V838 Mon (van Loon et al. 2004), a current understanding of photometric data of the progenitor star and modeling of light echo seem to conflict with the RGB/AGB/post-AGB hypothesis of the progenitor (Tylenda et al. 2005a). Rather, considering various possibilities, Tylenda et al. (2005a) argued that the progenitor of V838 Mon was a binary system of two main-sequence stars such as B1.5V and B3V, and that the interstellar material, which was brightened by light echo, does not originate from V838 Mon.

It is interesting to consider a scenario of the binary evolution, which produces an SiO maser star (late M supergiant) by an eruptive event. From the fact that we know already two examples of the eruptive formation of an M supergiant in the Galaxy: V838 Mon and V4332 Sgr (e.g., Banerjee et al. 2004). We estimate that the formation rate of this type of new class of nova events creating an M-supergiant after eruption is roughly one in every 10 years in the Galaxy. Because we could not detect any SiO maser emission in V4332 Sgr in the present paper, we assume that one of these two events creates an SiO maser star. It is hard to estimate the life time of maser emitting phase in V838 Mon. However, let us assume a rather buoyant value, 2000 years. In this case, we should observe 100 such maser stars of this kind in the Galaxy at any epoch of time. Furthermore, we know approximately about 1500 SiO maser emitting objects in the Galaxy (Deguchi et al. 2004b) and about 1000 OH/IR sources (Sevenster et al. 2001). Therefore, about 5–10% of these objects have the eruptive origin.

This is, of course, a very rough estimate, merely giving an order of magnitudes for such percentage. Furthermore, the galactic nova rate is difficult to estimate because of the patchy interstellar extinction (Shafter 1997). The largest uncertainty in the previous estimate seems to be involved in the time span of SiO maser emitting phase in V838 Mon at present. Because the SiO masers are emitted at

just a few stellar radii of the photosphere, it terminates within a few years when the mass loss ceases. Because once an AGB star is created (as a single star), its life time at the AGB phase would be longer than 10^5 years (depending on the mass). Therefore, it is not expected that the SiO maser terminates quickly unless the formed AGB-like structure is quite unstable and transient. It is quite interesting to know how long the SiO masers are detectable in V838 Mon and to know whether or not H_2O and OH masers follow in future.

We discussed the eruptive origins of maser stars based on the view point of a binary merger model of V838 Mon for simplicity. However, it should be noted that the above arguments are equally applied for an alternative scenario, i.e., the post-AGB progenitor being born again as an AGB star (Lawlor & MacDonald 2003), though the life span of the maser emitting phase must significantly be altered in such a scenario.

Spectroscopic observations suggested that V838 Mon is slightly metal deficient except with enhanced abundances of s-process elements (Kipper et al. 2004; Kaminsky et al. 2005). Among metallic species, Kipper et al. (2004) gave the Si abundance as 1/10 of the solar value, which does not seem to be consistent with the later finding of rich SiO infrared band emission (Rushton et al. 2005) and the SiO maser detection in the present paper. These facts may imply extreme difficulty of the abundance analysis from transient optical spectra. Alternative evidence of binary mergers in slightly metal poor environments was recently found in bulge globular clusters (Matsunaga et al. 2005); some SiO maser sources toward globulars are likely to be cluster members. Because luminosities of these objects slightly exceed the AGB luminosity limit of the low-mass objects expected in the aged globular clusters, these stars must be the objects created by binary mergers. In accounting these SiO maser sources in globulars, observations of maser sources do not necessarily constrain the mechanism whether it is a sudden, eruptive formation of an M-supergiant or it is a merger event in which a merged star evolved into the AGB phase in a certain period later. Statistics of SiO maser sources and blue stragglers in globulars may provide an answer to this question.

4. Conclusion

SiO maser emission from the eruptive variable, V838 Mon, was detected with the Nobeyama 45m telescope, confirming formation of a mass-losing M supergiant after nova eruption. The obtained radial velocity of masers, $V_{\rm LSR} \sim 54$ km s^{-1}, gives the first reliable evaluation of the radial velocity of this star, suggesting the kinematic distance of about 7 kpc for this object. If the SiO maser phenomenon in this star is persistent in a certain length, a considerable percentage of the SiO maser stars in the Galaxy may originate though the same mechanism, i.e., eruptive formation of maser stars from merged binaries. This observation approves evidence of the SiO maser phenomenon occurring in diversely different types of objects.

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